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Abstract

Research and innovation have considerable, currently unquantified potential to reduce greenhouse gas emissions by, for example, increasing energy efficiency. Furthermore, the process of knowledge transfer in itself can have a significant impact on reducing emissions, by promoting awareness and behavioural change. The concept of the 'carbon brainprint' was proposed to convey the intellectual contribution of higher education institutions to the reduction of greenhouse gas emissions by other parties through research and teaching/training activities. This paper describes an investigation of the feasibility of quantifying the carbon brainprint, through six case studies. The potential brainprint of higher education institutes is shown to be significant: up to 500 kt CO_2e/year for one project. The most difficult aspect is attributing the brainprint among multiple participants in joint projects.

Keywords: carbon brainprint, carbon footprint, universities, research, higher education, greenhouse gas.

1 Introduction

The need to reduce greenhouse gas (GHG) emissions is widely, though not universally, accepted. In the Climate Change Act 2008, the UK Government committed the country to reducing its GHG emissions by 34% by 2020 and 80% by 2050. These targets require action to reduce GHG emissions from all sections of the economy, including universities, which are expected to cut their own carbon footprints in line with these national targets (HEFCE, 2010). These emissions vary widely with the size and nature of the institutions: annual GHG emissions by universities from fuel and energy consumption in 2005 were 1–90 kt CO_2e/institution (SQW, 2010). This concern is part of a wider trend for universities, like other business, to study and improve their environmental performance (Baboulet and Lenzen, 2010).

The process of quantifying their own emissions has led universities to consider the possibility of measuring the contribution of research to reducing the emissions of other organisations. Universities could have an impact through research leading to new technologies, the transfer of the results of past research into practice, developing novel ways to promote behavioural change, and training and education to provide the necessary knowledge and skills to effect change. The carbon footprint is a commonly-used measure of the total set of GHG emissions caused directly and indirectly by an individual, organisation, event or product, although the definition and the boundaries used vary between studies according to their context and purpose (Pandey et al., 2011). The phrase 'carbon brainprint' was first proposed as an analogue of the carbon footprint to describe the wider impact of universities on GHG emissions emissions by the Deputy Chief Executive of the Higher Education Funding Council for England (HEFCE) during consultation on its GHG emissions reduction targets.

The objectives of the Carbon Brainprint project were to test whether it was possible to quantify the carbon brainprints of university activities, explore the difficulties in doing so, propose procedures and estimate the potential brainprints of several examples. This paper will summarise the general approach, briefly describe the case studies used to develop the concept, discuss what was learned from the case studies and identify some of the remaining problems in developing a general method for all types of university activities.

2 Methods

2.1 Case-study approach

As the objectives required development and testing of a method to quantify a previously conceptual measure, a multiple case study approach was adopted, in which the method evolved during the case studies. This approach was selected in preference to defining a method in advance, so that it could respond to the insights gained and test the underlying concept not the implementation.

The case studies were selected in advance to provide a diverse set of examples, encompassing technological interventions, training courses, detailed modelling and influencing behaviour (Table 1). All the cases were expected to have some impact on carbon footprint reduction, but only one (training for landfill gas inspectors) had quantified it. In addition to the technical differences between the cases, the type of engagement of the universities with the users varied, including implementation within the university campuses, long term research and development contracts with single customers, 'pure' research that had yet to be put into practice, and public sector consultancy relying on uptake by commerce to implement it. Each case was expected to provide different challenges to the methods being developed.

After completion, the case studies were reviewed individually and collectively to assess the need for revisions to the methods, areas of difficulty and conclusions related to the overall aims.

Table 1. Initial case studies

Project	University
Ceramic coatings for jet engine turbine blades to improve engine efficiency	Cranfield
Improved delivery vehicle logistics to save fuel	Cranfield
Training for landfill gas inspectors to improve methane capture	Cranfield
Novel offshore vertical axis wind turbines compared to conventional turbines	Cranfield
Intelligent buildings for energy management	Reading
Optimising defouling of oil-refinery preheat trains to reduce fuel consumption	Cambridge

2.2 Guidelines

A set of initial principles or guidelines for the case studies was drawn up by members of the project team, guided by the project steering committee and revised following the case studies. These principles were based on established approaches to carbon footprinting, including PAS 2050:2008 (BSI, 2008) and the Carbon Trust good practice guide (Carbon Trust, 2009), which are underpinned by guidance from the Intergovernmental Panel on Climate Change (Eggleston et al., 2006) and the methods of life cycle assessment (LCA) (e.g. Pennington et al., 2004; Rebitzer et al., 2004). However, as the intention was to obtain an estimate of a change in total emissions, it was anticipated that the level of detail would be coarser than that needed for an LCA of a specific functional unit, and that parts of the footprint unaffected by the change could be neglected. Indeed, it has been noted that, while footprints generally should be based on LCA, they have different characteristics, because they "have a primary orientation toward non-LCA experts and society in general", whereas LCA is designed for technical experts using indicators that "are not necessarily the lens through which society views environmental protection" (Ridoutt et al., 2015).

The guidelines divided the process of conducting a study into five main stages: system definition, boundary definition, data gathering, assessment and uncertainty analysis.

System definition should begin with an interview with the main academics who carried out the work, from which a general qualitative summary would be written describing the case, its application and expected impact. The *boundary definition* should follow from this, specifying the process, spatial, temporal and conceptual boundaries of the system being considered. It was anticipated that the boundaries would need to be drawn widely: in principle they would include all upstream and downstream emissions over a long time period. As the estimate was likely to contain significant uncertainty, a cut-off precision of 1% was suggested to avoid spurious precision.

Data gathering should include both the activity and emissions. The activity data would necessarily be specific to each case. Some emissions data would also be case-specific, but much could be found in standard sources such as the European Life Cycle Database (ELCD, 2010) and the UK guidelines (AEA, 2010).

The *assessment* of the change in emissions was the core of the methods being developed. As the aim was to assess the change in emissions, it could be achieved by several approaches depending on the data available, including directly evaluating baseline and changed emissions, evaluating baseline emissions and applying a proportional change to a component of the activity, or evaluating the change alone. The units to be used were mass of carbon dioxide equivalent, using the global warming potential (GWP) with a 100 year time horizon (GWP100). Depending on the context it might be appropriate to give a lifetime total, and annual quantity, or both. For an intervention or development in the past, data about its uptake or rate of use should enable assessment of its impact to date, referred to as the 'retrospective brainprint' with reasonable confidence. More recent developments would rely for their impact on future uptake, implying much greater degree of uncertainty in their potential results, known as the ‘prospective brainprint’.

Uncertainty analysis is required as part of national GHG inventories (Eggleston et al., 2006), and the carbon brainprint contained additional sources of uncertainty, particularly in the prospective brainprint, so the same approach should be followed as far as possible. The usual method is to define distributions for the main variables and parameters from data or expert judgement, then use Monte Carlo simulation to derive output distributions and present the results as the mean and 95% confidence interval.

One issue that was identified in the guidelines, but not fully resolved, was the attribution of the brainprint between multiple participants. When there were multiple university participants, it was proposed that this could be based on the share of the research income, or their documented roles. Indeed, if the aim was to estimate the impact of the university sector, there would be no need for finer attribution. Dealing with other participants whose roles went beyond implementation and uptake was anticipated to raise further difficulties.

3 Case studies

The case studies will be summarised, with emphasis on their contribution to the development of the method. Full details can be found in the project report (Parsons et al., 2011).

3.1 Ceramic coatings for jet engine turbine blades

The aviation industry is estimated to contribute about 2–2.5% of GHG emissions, and the number of aircraft in service is projected to double between 2011 and 2031 (Grote et al., 2014). Reducing emissions from aircraft through both operational changes and improvements in efficiency is, therefore, an important part of overall GHG emissions reduction. The Surface Science and Engineering Group at Cranfield University has been working with Rolls-Royce plc for over 17 years to improve the insulating performance of ceramic thermal barrier coatings (TBCs), which are applied to jet turbine blades to protect them from the high temperature gases leaving the combustion chamber and to increase the efficiency of the engine. As a result, the TBCs used in the current generation of aircraft turbofan jet engines permit operation at a temperature drop about 80 °C greater than prior to the research, with an estimated fuel saving of about 1% (inferred indirectly from other information). This case study considered two engine types: the Trent 700, used on about half of the Airbus A330 aircraft currently in service, and the Trent 500, used on all Airbus A340-500 and A340-600 aircraft.

Good data on the numbers of aircraft delivered and in service was available from (Airfleets, 2011) and full data on existing orders came from (Airbus, 2010). The activity data was statistical summaries of the number and distance of flight legs derived from the Association of European Airlines (AEA) via another university project (C. Miyoshi, personal communication). In the absence of other data, these were assumed to be typical of all operators.

No fuel consumption data was available from the operators, so it was modelled using publicly available estimates (EMEP/EEA, 2009) for the cruise phase standard engine tests for take-off and landing (CAA, 2010). The emissions during extraction and refining of the fuel were taken from (ELCD, 2010). Estimates of the emissions associated with fuel transport and manufacture of the blades showed they were negligible in comparison with the direct emissions.

The estimates of the current emissions reductions for individual aircraft were 1016–1646 t CO_2e/year depending on the model, giving a total retrospective GHG emissions reduction of 568 kt CO_2e/year (95%: 429–721) for the aircraft in service. Including all the aircraft on order, the mean prospective GHG emissions reduction was 833 kt CO_2e/year (95%: 629–1060). Assuming a service life of 20 years, the total brainprint was approximately 16 Mt CO_2e (95%: 12–20). More recent developments by the same team are included in newer engine models and aircraft, so these totals are substantial under-estimates.

This case study raised few conceptual challenges, because it concerned an incremental development in a well-studied field. It exemplified the large absolute values (relative to the other case studies) that could be obtained from small changes in energy-intensive processes. There was a residual uncertainty over the estimate of the change in efficiency, which had to be inferred in the absence of experimental data. The assessment required a relatively detailed, process-based model, similar to an IPCC Tier 3 assessment (EMEP/EEA, 2009). Using operational consumption data (Tier 2) would have simplified the study and reduced some of the uncertainties. The research was the work of a single university team, so the full brainprint was attributed to the university. This study raised the question of rebound effects, in which increased efficiency led to lower fares, resulting in more air travel. As there was no way to establish a causal link, and many other factors influence the use of air travel, this was excluded from the assessment.

3.2 Novel offshore vertical axis wind turbines

Researchers within the School of Engineering at Cranfield University were part of a consortium to develop further the concept of Novel Offshore Vertical Axis (NOVA) wind turbines. These turbines have greater potential power capacity than conventional horizontal axis turbines (HAWTs) and have a lower rotation speed and a more accessible hub, which allows for reduced emissions from maintenance over the turbine life cycle. The design has been optimised to a much higher power rating than current models of HAWT, so fewer turbines would be required for the same theoretical power output. It is expected that GHG emissions for an installation of NOVA turbines would be lower than for conventional HAWTs with the same output.

This project was still in its development stages, so there were no NOVA turbines in operation, and the brainprint was entirely prospective, based on the results of an LCA that was conducted during the project. The mean estimated total reduction in GHG emissions over a lifetime of 20 years was 102 kt CO_2e for installation of 1 GW rated power, from a baseline for the HAWT installation of 520 kt CO_2e.

This case study raised several difficulties with purely prospective assessments. There were large uncertainties in many variables, giving a 95% confidence interval for the lifetime (construction, operation and maintenance and decommissioning) reduction in GHG emissions of -111–315 kt CO_2e. The large uncertainty, including the possibility of an increase in emissions, arises because this is the difference of two random variables that are treated as independent. In practice, common features of the two types of installation mean that there is likely to be a positive correlation, which would reduce the variance of the difference. It should also be noted that the LCA used in this estimate considered a single type of HAWT, whereas an LCA of five types of HAWT found a range of 18–31 g CO2e/kWh generated (Raadal et al., 2014), which is an additional source of uncertainty. (Direct comparison of the two LCAs is difficult due to differing assumptions and choice of functional unit, but Raadal et al. appear to estimate much higher total emissions.) A fundamental uncertainty not included in this estimate was whether any installations would be built. Although there is value in estimating the potential environmental benefits of current research, it would be unwise to make strong claims on this basis until field trials could provide data to reduce the uncertainties and realistic projections of uptake were possible.

As the project had multiple participants, there was a need to consider attribution if the brainprint was to be divided among them. Based on the composition of the team and the division of the budget, Cranfield University's contribution was estimated to be one-third, or 34 kt CO_2e. This assumed that the brainprint was attributed entirely to the research institutions. If some of the innovations were contributed by the commercial partners in the consortium, it can be argued that the total university share should be reduced.

3.3 Improved delivery vehicle logistics

A Cranfield University PhD graduate and visiting fellow (Dr Andrew Palmer), contributed to transport recommendations for the food distribution industry (Faber Maunsell, 2007; Fisher et al., 2010), which were taken up by the food and grocery industry body IGD in the Efficient Consumer Response (ECR) initiative and implemented with 40 leading UK brands (IGD, 2011a). IGD reported that this initiative had reduced vehicle use by approximately 163 million road miles (2.6×10^8 km), or 80 Ml of diesel fuel, in the UK over approximately four years to the date of the report in early 2011. The target was 200 million road miles (3.2×10^8 km) by the end of 2011 (IGD, 2011b), by maintaining the reductions that had been achieved. Using an emission factor of 3.1787 kg CO_2e/l including indirect emissions (AEA, 2010), saving 80 Ml of fuel is equivalent to a GHG reduction of 250 kt CO_2e. Applying a standard emission factor to the reduction in distance travelled gave a similar result.

The main uncertainty in these estimates was the distance travelled, or fuel use. (Wiltshire et al., 2009) suggest using a coefficient of variation (COV) of 2% for distances and 10% for fuel use per km. As the estimates provided were for the reduction in distance travelled, with additional uncertainties, a normal distribution with mean 250 and COV 15% was used, giving a 95% confidence interval of 177–323 kg CO_2e/kg.

In the short term, the best estimate of the future reduction is the average for the period reported: 63 kt CO_2e/year. In the longer term, other changes in transport practice are likely to be introduced, and fuel efficiency is expected to improve (McKinnon, 2009), which would reduce the change in emissions from these measures. Conversely, the success of ECR may lead to similar measure being adopted by other operators both within and outside grocery distribution as part of wider sustainability initiatives, especially as studies show that 'green logistics' is neutral (Pazirandeh and Jafari, 2013) or beneficial (Ramanathan et al., 2014) for operational and financial performance. This raised the question of whether indirect reductions of this type should be included. The steering committee agreed to follow the practice of the Carbon Trust and exclude indirect reductions.

This case study again highlighted the question of attribution, as the authors of the underpinning report, other than Dr Palmer, were from Faber Maunsell (a consultancy business) and Heriott Watt University. From discussions with Dr Palmer, he was a main contributor to two of the six recommendations and contributed to the other four. An estimate of 30% was therefore used for attribution to him. Although not an employee of Cranfield University, the majority of his contribution was based on his PhD or work at Cranfield, so an estimate of 75% was used. Combining these, the mean estimate of the retrospective brainprint attributable to Cranfield was 56 kt CO_2e, or 14 kt CO_2e/year, with greater uncertainty than the aggregate figure.

3.4 Landfill gas inspector training

This case study considered the impact of a training course, run by academics at Cranfield University in 2008 on behalf of Environment Agency (EA) of England and Wales. The training was a technical course for landfill gas inspectors to improve the recovery of methane at existing landfill sites. Landfill gas is the largest source of methane emissions in the UK: of the estimated UK total methane emissions of 2330 kt in 2008, 966 kt (24 Mt/CO_2e) came from landfill (NAEI, 2011). The course trained 12 EA officers, and drew on the knowledge of a retired EA landfill gas expert in addition to Cranfield staff. At the end of the course, the trainees split undertook 24 site visits, making recommendations for improved methane recovery, such as surface capping, gas well installation or replacement and pipeline maintenance or balancing. A second course was subsequently run for an additional 12 officers.

The EA assessed the results of the initial set of 24 site visits and estimated that the measures taken had resulted in the collection of an additional 7,600 m^3/hr of landfill gas. The EA suggested using a conservative estimate of 40% v/v for the methane content, giving 26.63×10^6 m^3 methane/year. Assuming a methane density of 0.68 kg/m^3 at 15°C and standard atmospheric pressure yielded 18.1 kt/year of methane, equivalent to 453 kt CO_2e/year using the standard GWP of 25. However, the methane collected would ultimately be burned, emitting carbon dioxide, so the estimated net reduction in GHG emissions was 403 kt CO_2e/year.

Achieving this reduction required the installation of additional equipment, mainly medium-density polyethylene (MDPE) piping. Combining data on the MDPE used in the largest of nine sites in a separate best-practice study (Raventós Martín and Longhurst, 2011) with an LCA for MDPE (Baldasano Recio et al., 2005), the total emissions for the piping were calculated to be less than 1.5 kt CO_2e. This was less than 1% of the gas captured from each site in one year, so no estimates of equipment life cycle emissions were included in the brainprint calculations. Indirect benefits that could be obtained by using the gas to displace fossil fuels were excluded.

There was no data on the work of the first group of trainees after the initial set of visits, or on the second group. The initial interventions would continue to reduce emissions, but the rate of production of methane within the landfill might change over time, and the gas recovery on subsequent sites might be lower due to the selection of the initial set. Assuming the gas yield deceased by 10%/year and that each group made a similar set of visits, but achieved only 70% of the reduction obtained in the first year, the total reduction in GHG emissions in year 2 compared with the status quo would be 927 kt CO_2e, or a cumulative total of 1,330 kt CO_2e. Extrapolating forward for an additional three years, assuming similar decreases in results, the cumulative emissions reduction over five years would be 5,380 kt CO_2e.

In the uncertainty analysis, the change in emissions reported by the EA was treated as certain, but, based on a survey of seven UK landfill sites (Allen et al., 1997), a uniform distribution in the range 36–64% v/v was used for the methane concentration of the gas. This resulted in a 95% confidence interval for emissions reduction in the first year of 370–638 kt CO_2e. All of the other variables – the numbers of future visits, their effectiveness and the resulting changes in emissions – were assumptions without supporting data, so were treated as highly uncertain and given independent normal distributions with coefficients of variation of 50%. The resulting 95% confidence intervals were 1,090–1,570 kt CO_2e for the first two years and 3,700–7,310 kt CO_2e for the five-year total.

The fact that the EA had audited the results of the first training cohort enabled a straightforward and reliable estimate to be made of the total brainprint of this activity. It highlighted the impact that interventions affecting methane could have, due to its high global warming potential. Beyond the first year, the extrapolation entailed large uncertainties. The other main difficulty with this case study was attribution. The course was managed by Cranfield University and taught by its staff, but included knowledge experience from EA staff. The steering committee took the view that the course would not have taken place without the involvement of a university or similar institution, so the brainprint could be attributed solely to the university. However, there is also a case for dividing it between the university and the EA.

3.5 Intelligent buildings

Over the past 20 years many different buildings have been labelled as “intelligent” (Clements-Croome, 2004). Industry has many established intelligent building solutions but finds it difficult to demonstrate and prove their benefits. The ideal system links the building, systems within it and the occupants so they have some degree of personal control. Intelligent controls help to match demand patterns (Noy et al., 2007; Qiao et al., 2006). It has been demonstrated that effective action on GHG emissions requires building users to be involved in both the process and the operation, so that they feel part of carbon management plans (Elmualim et al., 2010).

A team consisting of researchers at the University of Reading, the University’s Facilities Management Directorate, Newera Controls Ltd. and Carnego Systems Ltd. conducted two separate investigations to measure and demonstrate the potential for two important and complementary approaches for achieving energy efficiency and GHG emission reductions in buildings. This study was unique within the project in involving new research rather than analysis of the results of previous projects.

The first investigation focused on saving electricity used for lighting, office equipment and catering by influencing user behaviour in an office building on the main campus. Electricity consumption was recorded over a 7 month period (October–April) in the trial, with each month divided into occupied days and unoccupied days. The results were compared with the same period in the previous year, having standardised both to an occupancy of 20.5 days/month. The reduction in emissions from electricity generation and distribution, using a conversion factor of 0.61707 kg CO_2e/kWh (DECC, 2010), was 7.8 t CO_2e from a baseline of 38.4 t CO_2e, a reduction of about 20%. Although the uncertainty in the measured consumption was low, the comparison with the baseline introduced uncertainty due to the differences in occupancy, weather and other influences on behaviour.

The second investigation considered an interventionist approach in an accommodation block at the Henley Business School using intelligent monitoring and control systems. The existing Building Management Systems was enhanced using a Building Energy Management System to control some of the system parameters for occupied rooms and reduce the heating in unoccupied rooms. By comparing the results with another block before and during the trial, energy savings in the form of heating oil were estimated to be about 25%. The reduction in emissions was estimated to be 3.3 kg CO_2e/day, but this was highly variable due to changes in occupancy and weather. The change would be much lower during the summer, but additional savings could be made if the system was extended to other services, such as lighting.

Given the uncertainty and variability present in both sets of data and the limited duration, the results were not extrapolated to a carbon brainprint for a whole year or a longer period. On the evidence of these two investigations, measures of this type could reduce non-domestic energy consumption by of the order of 20–25%. A detailed carbon footprint study of one UK university found that building energy use accounted for one-third of its total GHG emissions, of which half were from electricity use in buildings owned by the university (Ozawa-Meida et al., 2013), so the potential reductions within university estates are significant. Many of the same measures could be applicable to other non-domestic buildings, which are responsible for 20% of the UK's GHG emissions (Choudhary, 2012), but the total impact would be highly dependent on uptake.

3.6 Optimising heat exchanger cleaning to reduce fuel consumption in oil refineries

Although the largest proportion of GHG emissions from the use of fossil fuels arises from their combustion, the direct and indirect emissions during refining can account for up to 14% of the life-cycle emissions for petrol/gasoline (Elgowainy et al., 2014). Heating the crude oil from ambient temperature to its bubble point (360–380 °C) prior to fractional distillation is the major energy consumer amongst all distillation processes in the chemical and petroleum industries (Humphrey et al., 1991). About 60–70% of the heat (Panchal and Huang-Fu, 2000) is recovered from the hot product streams of the crude oil distillation unit in a series of heat exchangers, known as the preheat train, prior to entering the furnace. Without the preheat train, 2–3% of the crude oil throughput would be used for heating the furnace. To maintain their efficiency, the heat exchangers need to be cleaned periodically, during which the performance of the preheat train is reduced.

Research in the Department of Chemical Engineering and Biotechnology at the University of Cambridge funded by the Engineering and Physical Sciences Research Council used a model of the preheat train to optimise the cleaning schedule, subject to constraints on the temperature at several points (Ishiyama et al., 2010, 2009).

Two refineries for which the necessary data were available were considered in the study: a Repsol YPF refinery in Argentina and the Esso Fawley Refinery in the UK. Simulation studies were conducted with and without optimised cleaning schedules to estimate the difference in fuel use for heating. The only emissions considered were those arising from direct combustion of oil products to heat the crude oil prior to distillation, calculated using a stoichiometric method based on the fuel composition. The predicted changes were small fractions of the total throughput of the refinery, so the resulting change in total output was neglected.

The analyses simulated a three year period for the Repsol YPF case and two years for Esso Fawley. Compared with current practice, systematic cleaning at the Repsol YPF refinery was predicted to result in an average GHG emissions reduction of 1.0 kt CO_2e/year. If the desalter inlet temperature was constrained, the emissions reduction was 0.77 kt CO_2/year. For the Esso Fawley refinery, the predicted average reduction in emissions with systematic cleaning was 1.4 kt CO_2/year.

The differences between the two refineries studied in terms of throughput and configuration show that it is not possible to extrapolate directly from these results to other installations, however, from the results obtained, a realistic estimate of the likely GHG emissions reduction for each refinery is of the order of 1 kt CO_2/year. There were no implementations in practice that could demonstrate this, but the university was working with the company IHS-ESDU to include the algorithm in a commercial software product.

The estimation in this case was simple, as the existing model included most of the necessary calculations. Within the model, the furnace efficiency was the main source of uncertainty. Both results assumed a furnace efficiency of 90%; if the efficiency was lower, greater reductions in emissions would be obtained.

4 Discussion

The Carbon Brainprint project aimed to develop and make available robust methods to calculate both retrospective and potential estimates of the contributions that universities make to reducing GHG emissions. Six contrasting case studies were used to develop and test the methods, and to provide an indication of the benefits that might be obtained. The magnitude of the retrospective brainprints varied widely between case studies, from about 12 t CO_2e/year to over 500 kt CO_2e/year (Table 2). The large absolute values were often the result of small changes in efficiency in processes with high emissions. Although larger proportional reductions in emissions were found in other studies, these were pilot studies, so the absolute values were small, though the future potential if they were adopted is very large. It was clear from the landfill gas case study that interventions to reduce GHGs other than carbon dioxide can have very large impacts due to the high GWP of the gases considered.

Case studies in which changes in emissions or activity had already been measured provided the clearest demonstration of the benefits of innovation or knowledge transfer to GHG emission reduction. These cases were also simplest and least uncertain to evaluate, as they allowed a direct calculation. Where such results had not been recorded, even for an existing innovation, such as turbine blade coatings, it was necessary to use a model-based (Tier 3) approach, which was considerably more time-consuming and contained many sources of uncertainty. Inevitably, extrapolation to future impacts required a model, however simple, and introduced many new uncertainties. If universities wish to provide a clear demonstration of the impact of their work, some engagement with the users after implementation to collect operational data would greatly simplify the process and provide the most reliable evidence.

In most cases, the change in emissions during operation far outweighed emissions involved in the application of the innovation. The exception was the NOVA turbine study, in which the bulk of expected emissions would occur during construction and installation. It therefore required a full LCA, but fortunately an existing LCA model was available.

The most contentious issue in several studies was attribution of the brainprint among different parties. Although it was recognised that the development and implementation are vital, the steering committee concluded that the brainprint attributed to the research or training team should include the full reduction in emissions, as it provided the foundation for all that followed. Where the research involved collaboration between several higher education or research sector parties, simple methods, such as considering the proportions of the research budget or documented project roles could be used. Indeed, to assess the overall benefits of universities, it is not necessary to attribute the brainprints to individual institutions, though the institutions might have their own interest in doing so. Furthermore, if the contribution of the non-university parties was similar in nature to that of the universities (e.g. the transport logistics case study), the same method could be applied. The most difficult cases were where there was a distinct contribution from non- university participants that went beyond providing funding or implementing the results of research, for example the training for landfill gas inspectors. One point of view was that if the benefits could not have been realised without the university (or an equivalent) then the full brainprint could be attributed to the university, and the results shown reflect this. If the intention was to make a comparison between different universities, this might be adequate. However, this view may fail to recognise the intellectual contribution from other parties and overestimate the role of universities in total. Further work is needed to develop a more rigorous method of attribution.

All of the case studies were initially proposed because they were expected to result in a reduction in GHG emissions, which left open the question of whether other activities might result in increases. In general, energy efficiency meets both business and environmental objectives, and public policy supports reductions in GHG emissions and improved sustainability in general, so these are well-funded areas of research. Nevertheless, it is possible that research and development with other objectives, or even in pursuit of these aims, could have side effects that increased GHG emissions. The same methods could be applied to quantify these. As with the GHG emissions reductions, only a few activities with large impacts are likely to be significant, so the scope of a complete review could be limited by identifying any projects likely to result in large increases in energy consumption or emissions of methane and other potent GHGs.

Table 2. Summary of case study total annual emissions reductions (without attribution to specific universities)

Project	Emissions reduction, kt CO_2e/year	Period
Ceramic coatings for jet engine turbine blades to improve engine efficiency	570	Retrospective
Improved delivery vehicle logistics to save fuel	63	Retrospective
Training for landfill gas inspectors to improve methane capture	400	Retrospective
Intelligent buildings for energy management	$\ll 1$	Retrospective
	Potential 20% reduction in CO_2e	Prospective
Novel offshore vertical axis wind turbines compared with conventional turbines	1.7 for 1 GW installed	Prospective
Optimising defouling of oil-refinery preheat trains to reduce fuel consumption	~1 per refinery	Prospective

5 Conclusions

The results of the project met the original objectives by using case studies to develop procedures, which could be applied more widely, to quantify the external benefits of some university activities in reducing GHG emissions, termed the carbon brainprint. The estimated emissions reductions already achieved from single projects were up to 570 kt CO_2e/year. The six projects were selected for study because they were expected to produce reductions in GHG emissions, so the large reductions seen in three cases are probably relatively rare compared with the more modest results found in the others. Whilst the carbon brainprint should not be used to offset an institution's carbon footprint (up to 90 kt CO_2e/year), it provides an additional method for universities to evaluate and demonstrate their wider impact.

The main difficulty identified in the case studies was the method of attribution amongst multiple parties, especially when some were from outside the university and research sector. This still needs further development. The case studies only included research, consultancy and training with fairly direct links to outcomes. The benefits of general educational activities were not addressed and would be difficult to quantify.

The project highlights the significant contribution of universities to reducing the GHG emissions of others, and should encourage further institutions to attempt to evaluate the brainprints of other activities.

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